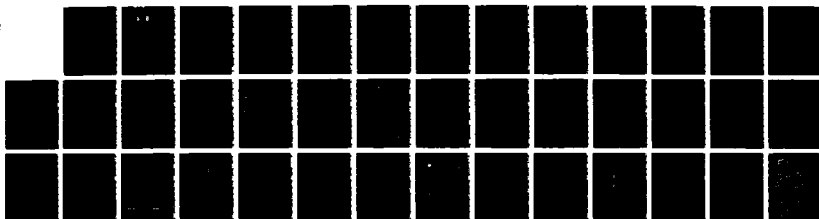


AD-A190 037 WAVE PROPAGATION AND DYNAMICS OF LATTICE STRUCTURES(U) 1/1
NEA CAMBRIDGE MA J H WILLIAMS 01 OCT 87
AFOSR-TR-88-0062 F49620-85-C-0148

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One of the most attractive structural configurations for large space structures (LSS) for outer space applications is the repetitive lattice concept. Achieving the operational requirements of such structures will necessitate considerable knowledge of the dynamics, control, materials and nondestructive evaluation (NDE) of these structural systems. Wave propagation analyses provide potentially valuable perspectives from which to consider this broad range of analysis, design and synthesis issues.

The theoretical and experimental results of a two-year research program on the wave propagation and dynamics of LSS are briefly reviewed. Potential benefits of wave propagation analyses in the vibration, parameter identification, dynamic failure, control and NDE of lattice structures have been identified and are summarized in this report.

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INTRODUCTION

Many papers and reports may be found in the literature on the concepts, design, analysis and potential uses of lattice structures in outer space. Such structures include large antennae, solar power systems and habitable stations for support of space colonies.

Currently, both deployable and erectable concepts are being investigated for the implementation of lattice structures. Also, investigations of size considerations indicate that small antennae ranging from tens of meters in span to solar power collectors ranging up to several thousand meters have been proposed. Such structural sizes along with stringent operational requirements will require considerable information of dynamics, control, materials, nondestructive evaluation (NDE), environmental effects and wave propagation relating to their design and analysis.

Much has been written on the theoretical aspects of the control of such structures. Also, a large number of vibration analyses have been undertaken. However, despite a distinct recognition of the importance of wave propagation in many of the control, vibration and NDE investigations, very little can be found on wave propagation in large space structures (LSS). The major goal of this program was to pursue the development of several aspects of wave propagation analyses in LSS.

ACCOMPLISHMENTS

A number of theoretical and experimental analyses have been undertaken. Some of these efforts have been documented in reports and some as yet remain undocumented in formal reports. The formally documented accomplishments will be described briefly.

As indicated above, the focus of our investigations has been the wave propagation of broadband and narrow-band signals in lattice structures for outer space applications. Theoretical and experimental analyses which have resulted in formal reports are listed here.

1. Theoretical formulations of the input-output relations for arbitrary pairs of locations on periodic structures have been initiated. In this formulation, we have used (and are continuing to use) a transfer matrix technique for analyzing periodic structures which can be modeled as one-dimensional continua, two-dimensional rectangular trusses and three-dimensional tetrahedral trusses. The elements in these structures are capable of transmitting longitudinal, shear and flexural waves. Our efforts on this topic have resulted in reports* as follows:

- J.H. Williams, Jr., H.K. Yeung and R.J. Nagem, "Joint Coupling Matrices for Wave Propagation in Large Space Structures", AFOSR/WEA Technical Report, April 1986
- J.H. Williams, Jr., R.J. Nagem and H.K. Yeung, "Wave-Mode Coordinates and Scattering Matrices for Wave Propagation in Large Space Structures", AFOSR/WEA Technical Report, October 1986.

* Reports written on this topic and other topics that were published on an earlier contract are relevant but are not listed here. For the listing of those reports, refer to J.H. Williams, Jr., "Wave Propagation and Dynamics of Lattice Structures", AFOSR/WEA Final Report, October 1985.

2. The dynamic properties of two two-dimensional lattice structures have been investigated both analytically, using the NASTRAN finite element code and transfer matrices, and experimentally, using an HP Fourier analyzer. The natural frequencies obtained via the three approaches were compared and shown to agree within seven percent of each other. These results are reported in a document as follows:

- J.H. Williams, Jr. and R.J. Nagem, "Computation of Natural Frequencies of Planar Lattice Structures", AFOSR/WEA Technical Report, March 1987.

More recently, this work has been extended to consider the nondestructive detection of damage and is reported as follows:

- J.H. Williams, Jr. and R.J. Nagem "Natural Frequencies and Structural Integrity Assessment of Damaged Lattice Structure", AFOSR/WEA Technical Report, April 1987.

Further, in these efforts we have collaborated with colleagues at Stanford University and Virginia Polytechnic Institute and State University. In fact, both 5-bay and 22-bay lattice structures which we have fabricated and tested have been sent to colleagues at Stanford for testing.

3. In lattice structures where the signal propagation is dominated by longitudinal waves, we hope to develop general closed-form expressions for the input-output relations of arbitrary pairs of locations of the structure. This type of analysis requires the reckoning of each wave front which leaves joint *i* and arrives at joint *j*, having undergone a series of reflections and transmissions at each intervening joint encountered along the way. Such an approach may be called a "wave summation analysis". We have been able to duplicate these results

using wave-mode coordinates. Our efforts thus far on this topic have resulted in a report as follows:

- J.H. Williams, Jr., R.J. Nagem and H.K. Yeung, "Comparison of Wave-Mode Coordinate and Pulse Summation Methods", AFOSR/WEA Technical Report, December 1986.

4. The wave propagation characteristics of a 5-bay aluminum planar lattice were studied experimentally. Wave propagation speeds and frequency spectra were obtained, and wave propagation reciprocity was observed. Wave propagation attenuation was quantitatively measured and an attenuation parameter expressed on a per-bay basis was defined. Similar results for a 22-bay structure are reported as follows:

- J.H. Williams, Jr. and J.J. Zhang, "Wave Propagation Measurements on 22-Bay Lattice", AFOSR/WEA Technical Report, June 1987.

5. One of the most distinctive uses of wave propagation versus modal analysis lies in the description of nonlinear behavior. Our work on dynamic failure and techniques for arresting such failure has provided a fascinating application of wave propagation analyses in LSS. This work is reported as follows:

- J.H. Williams, Jr. and R.J. Nagem, "Dynamic Failure of a Periodic Lattice Structure", AFOSR/WEA Technical Report, October 1985.

- J.H. Williams, Jr. and S.S. Lee, "Failure Propagation in Continuum Models of LSS, Part I", AFOSR/WEA Technical Report, November 1986.

- J.H. Williams, Jr. and R.J. Nagem, "Dynamic Failure Arrest in Lattice Structures Via Wave Deflectors", AFOSR/WEA Technical Report, December 1985.

- J.H. Williams, Jr. and S.S. Lee, "Failure Propagation in Continuum

Models of LSS, Part II", AFOSR/WEA Technical Report, February 1986.

- J.H. Williams, Jr. and R.J. Nagem, "Dynamic Failure Arrest in LSS Via Active Control", AFOSR/WEA Technical Report, July 1986.

6. When the wavelength is long compared with the length of lattice elements, continuum models may be used to provide computationally efficient analyses. Wave propagation in a tetrahedral lattice, which was modeled as a transversely isotropic continuum, was conducted to provide some insight into the nonintuitive behavior of long wavelength dynamics of LSS. This work is reported as follows:

- J.H. Williams, Jr., R.J. Nagem and K.G. Salamé, "Wave Propagation in Transversely Isotropic Continuum Models of LSS", AFOSR/WEA Technical Report, January 1987.

SUMMARY

While there continue to be misconceptions and misrepresentations of the wave propagation perspective of dynamics of LSS, the value of wave propagation analyses of dynamic phenomena in LSS is no longer an anomalous curiosity. In an attempt to assist in the enlightenment of the technical community regarding wave propagation in LSS, a presentation entitled "Wave Propagation in Large Space Structures" was presented at the Fifth AFOSR Forum on Space Structures in Monterey in August 1987. The abstract and the transparencies for that presentation are given as the appendix of this report.

APPENDIX

Wave Propagation in Large Space Structures

James H. Williams, Jr.
Raymond J. Nagem

Department of Mechanical Engineering
Massachusetts Institute of Technology
Cambridge, MA 02139

ABSTRACT

Waves and modes are discussed in the context of dynamics of large space structures. It is observed that wave propagation analysis is much more general than modal analysis, and that wave analysis can be applied to a much broader class of dynamic phenomena. Thus, some phenomena which can be conveniently described by wave propagation have no equivalent modal representation. In linear analysis, when wave propagation analysis and modal analysis are theoretically equivalent, the preference between a wave analysis and a modal analysis is assessed in accordance with the ratio of the wavelength of a typical disturbance function to the characteristic structural length. A definition of a large space structure is given in terms of the characteristic structural length and the typical disturbance wavelength. Recent research results in continuum modeling, scattering theory, control system design and dynamic failure are given to illustrate applications of wave propagation analysis in the dynamics of large space structures.

Sponsor: AFOSR
Program Manager: Anthony K. Amos

WAVE PROPAGATION IN
LARGE SPACE STRUCTURES *

James H. Williams, Jr.

and

Raymond J. Nagem

M.I.T.

(AFOSR: Anthony K. Amos)

* Because the original transparencies were multicolored, the quality of these copies is relatively poor.

**Recent Titles on
WAVE PROPAGATION IN LSS**

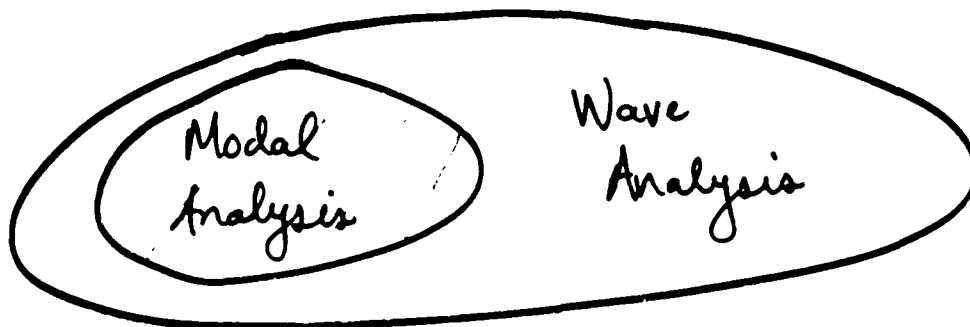
- Wave Propagation and Dynamics of Lattice Structures.
- Dynamic Analyses of Two-Dimensional Lattices.
- Wave Propagation Through T and L Joints.
- Nondispersive Wave Propagation in Periodic Structures.
- Feedforward Control of Waves in Lattice Elements.
- Wave Propagation Measurements on Two-Dimensional Lattice.
- Wave Measurements on Truss Model.
- Wave Propagation and Dynamics of Lattice Structures.
- Dynamic Failure of a Periodic Lattice Structure.
- Failure Propagation in Continuum Models of LSS, Part I.
- Dynamic Failure Arrest in Lattice Structures Via Wave Deflectors.
- Failure Propagation in Continuum Models of LSS.
- Joint Coupling Matrices for Wave Propagation in Large Space Structures.
- Dynamic Failure Arrest in LSS Via Active Control.
- Wave-Mode Coordinates and Scattering Matrices for Wave Propagation in Large Space Structures.
- Comparison of Wave-Mode Coordinate and Pulse Summation Methods.
- Wave Propagation in Transversely Isotropic Continuum Models of LSS.
- Pattern Recognition of LSS States Via Wave Propagation.
- Wave Propagation Measurements on 22-Bay Lattice.
- Computation of Natural Frequencies of Planar Lattice Structures.
- Natural Frequencies and Structural Integrity Assessment of Damaged Lattice Structure.

Topics of Current LSS Research Activities

- Scattering of Waves at Joints in LSS
- Nondestructive Evaluation of LSS
- Numerical Efficiency of Transfer Matrix Method for LSS Applications
- Wave Propagation in Anisotropic Continuum Models of LSS
- Control of Wave Propagation in LSS

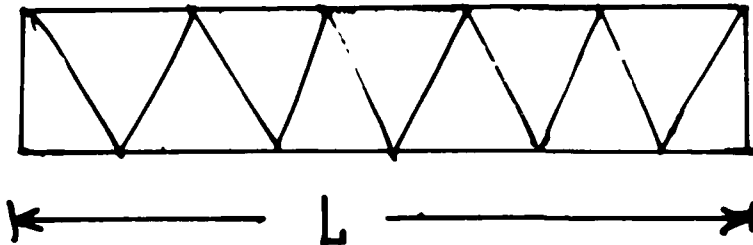
Modes vs Waves

Linear Elasticity vs Nonlinear Elastic-Plastic
Continuum Theory



	Modal Analysis	Wave Analysis
Linear Dynamic Response	✓	✓
Nonlinear Elastic Dynamic Response	X	✓
Dynamic Failure	X	✓
Short Pulse Discontinuous Systems	?	✓
Wave Control	?	✓

Linear Analysis



λ = wavelength of excitation
 c = wave speed in structure
 T = period of excitation
 L = characteristic length of structure

} $\lambda = cT$

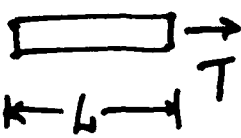
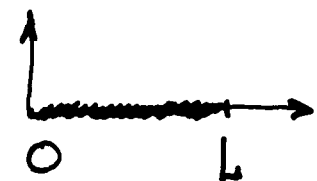
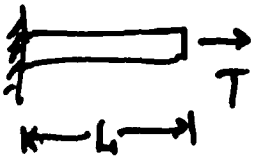
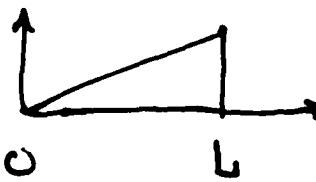
Regime	Probable Preference
$\lambda \gg L$	Statics or Rigid Body Dynamics
$\lambda \approx L$	Modes
$\lambda \ll L$	Waves

Long λ ($\lambda \gg L$)


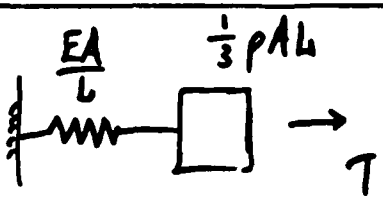
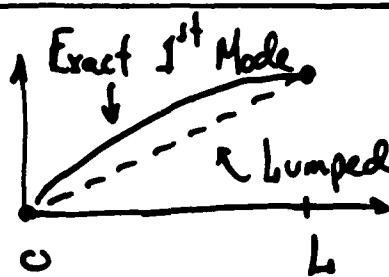
Response is Quasistatic Deformation
or Rigid Body Dynamics

Continuum models are useful

Structural details are not "seen" by
dynamic response

System	Excitation Condition $\lambda = cT$	Response	Model	Deformation Response
	$\lambda \gg L$	Rigid Body	Mass, ρAL	
	$\lambda \gg L$	Quasistatic Deformation	Spring, $\frac{EA}{L}$	

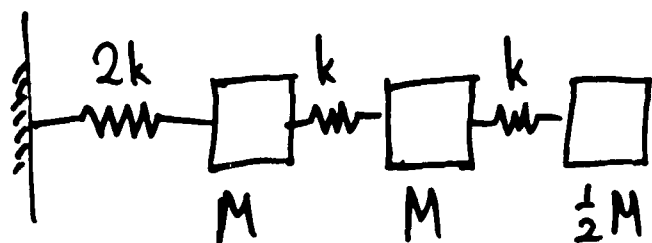
Intermediate λ ($\lambda \approx L$)

System	Excitation Condition	Response	Model	Deformation Response
	$\lambda \approx 4L$	Dynamic		

Exact: $\omega_n = 1.571 \sqrt{E/(\rho L^2)}$

Approximate: $\omega_n = 1.732 \sqrt{E/(\rho L^2)}$

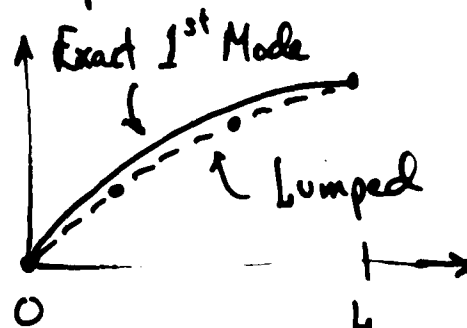
2nd Model



$$k = \frac{5EA}{2L}$$

$$M = \frac{2\rho AL}{5}$$

Deformation Response



Approximate $\omega_n = 1.545 \sqrt{E/(\rho L^2)}$

Short λ ($\lambda \ll L$)



$$\frac{L}{\lambda} \sim 100$$

How many modes are required to model this disturbance?

Can a control system designed to control the first twenty modes respond accurately to such an excitation?

LSS

"Large" means, by definition, $L \gg \lambda$

Consequences :

- Time lags are likely to be important
- Structural details become important
- Truncated modal summation may result in significant errors

Some dynamic behaviour has no modal description

Wave Propagation in LSS

In steel or aluminum, $c_{\text{shear}} \approx 10^4$ ft/sec

$$\lambda = cT$$

<u>T (sec)</u>	<u>λ (ft)</u>
10^{-5}	10^{-1}
10^{-4}	10^0
10^{-3}	10^1
10^{-2}	10^2

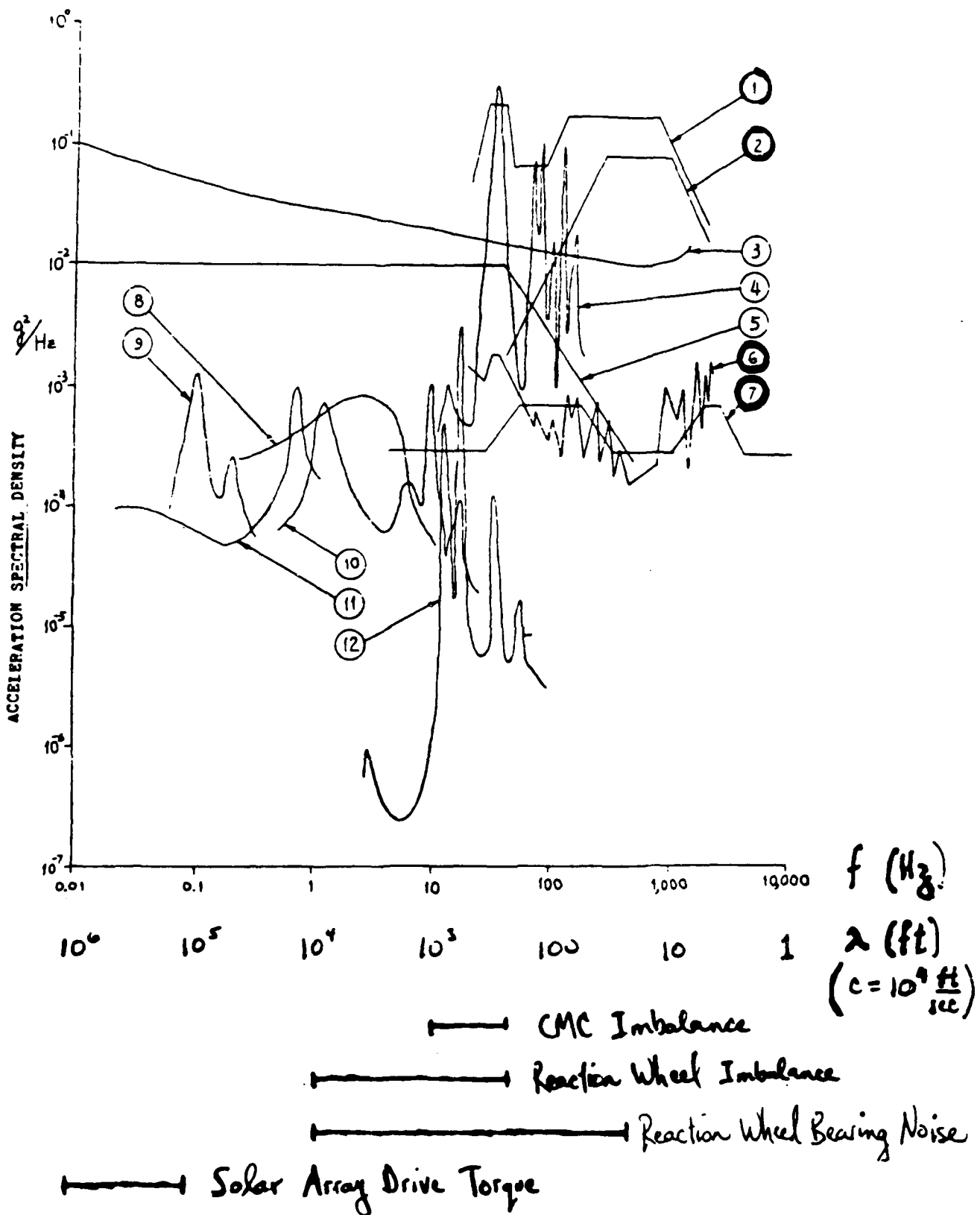
For a structure 10^3 ft long, an impact of duration 10^{-3} sec produces a disturbance with

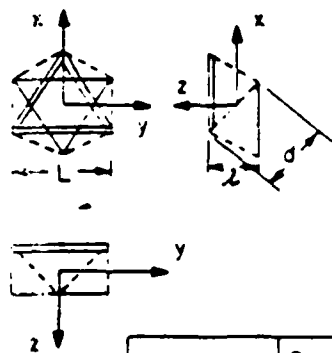
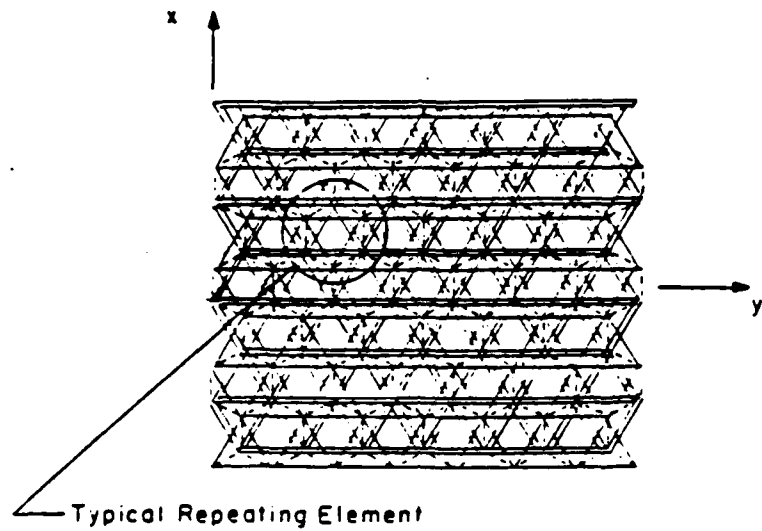
$$\frac{L}{\lambda} \approx 100$$

Criterion for Wave Propagation:

If the wavelength produced by a disturbance is much less than the characteristic length of the structure, then a wave analysis is likely justified.

Excitation Sources

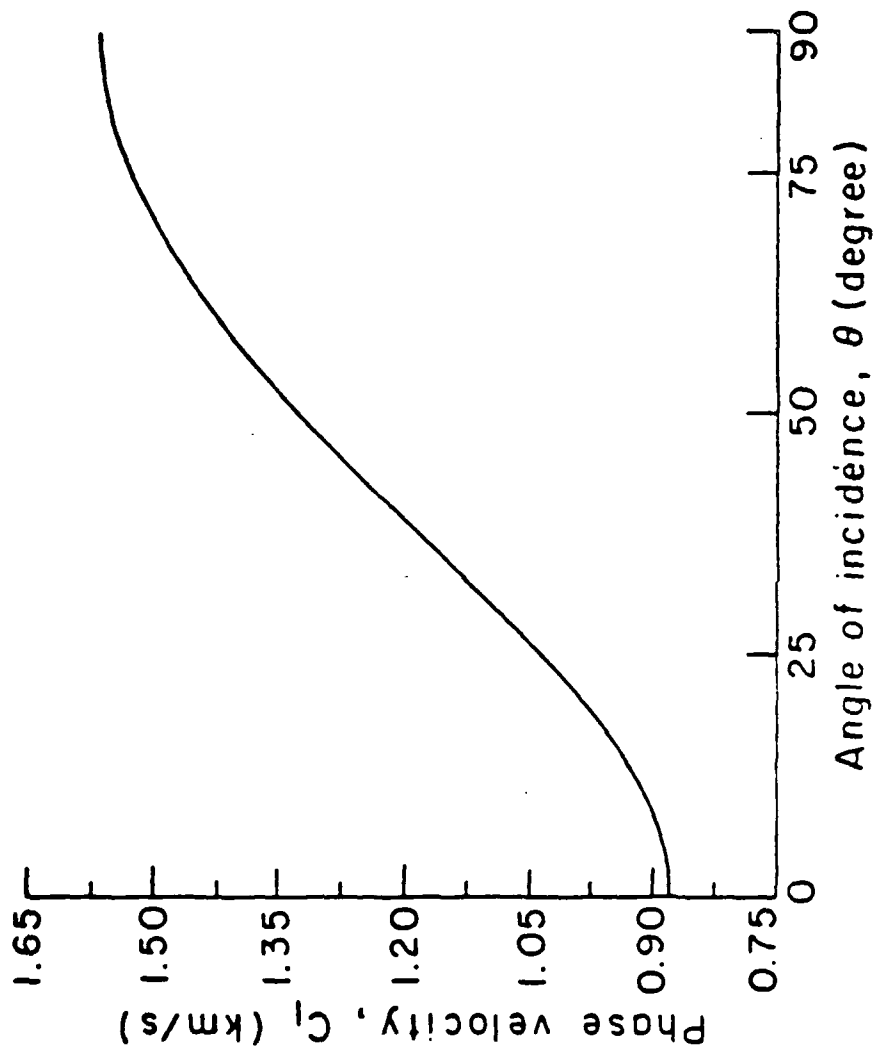




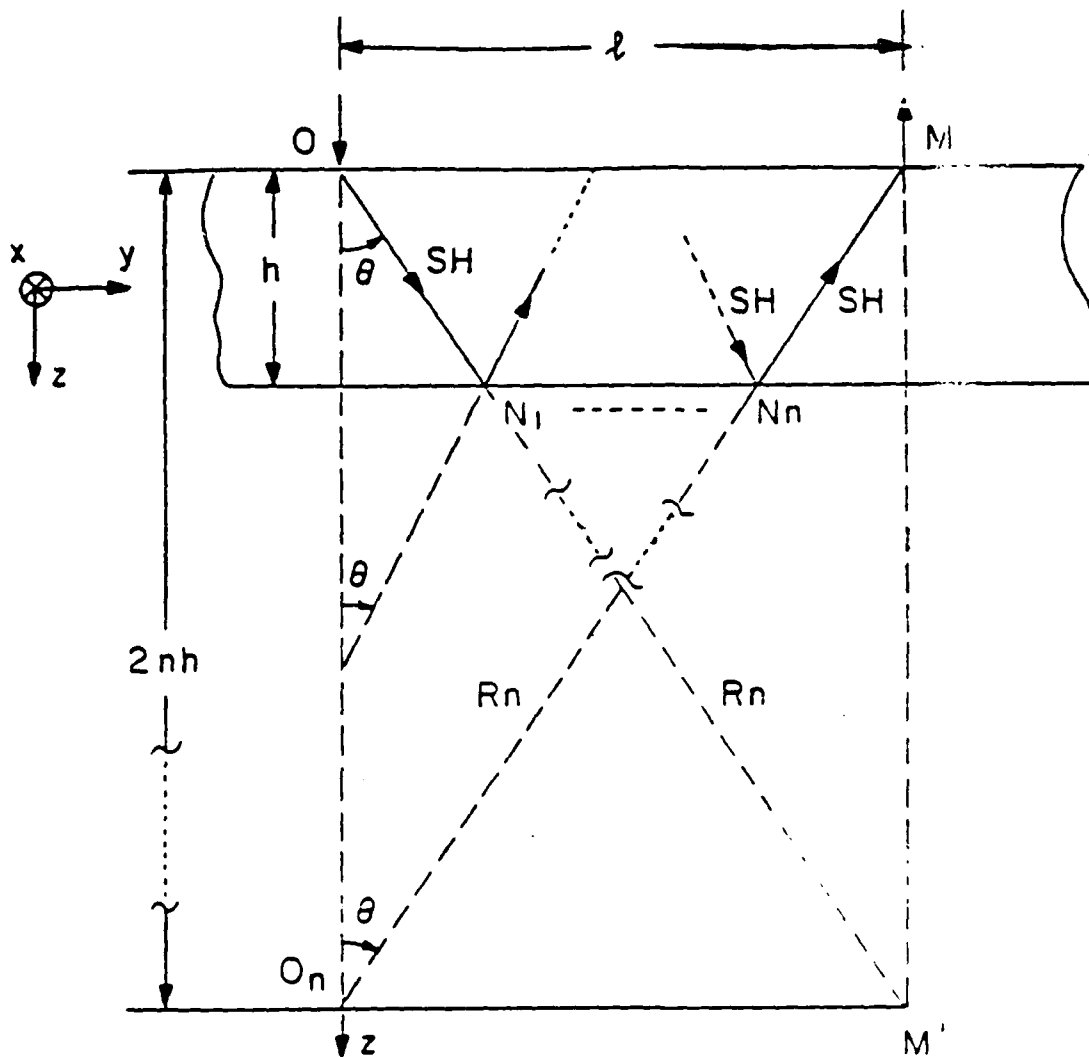
$$\begin{aligned}
 A &= 80 \times 10^{-6} \text{ m}^2 & L &= d = 7.5 \text{ m} \\
 A_d &= 50 \times 10^{-6} \text{ m}^2 & E &= 71.7 \times 10^9 \text{ N/m}^2 \\
 & & \rho_L &= \rho_d = 2768 \text{ kg/m}^3
 \end{aligned}$$

	Cross Sectional Area	Length	Material Density	Symbol
Top Surface Bars	A	L	ρ_L	\equiv
Bottom Surface Bars	A	L	ρ_L	---
Bracing Bars	A_d	d	ρ_d	----

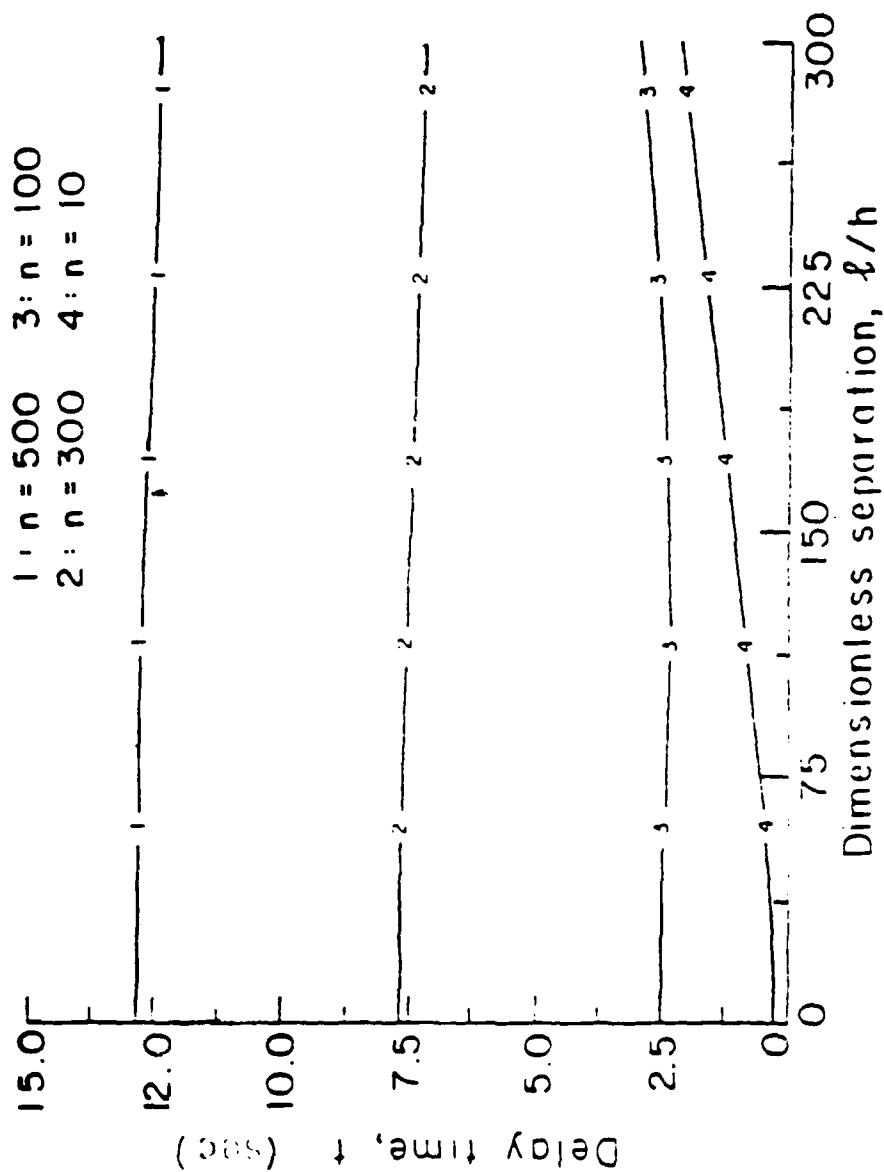
Tetrahedral lattice structure.



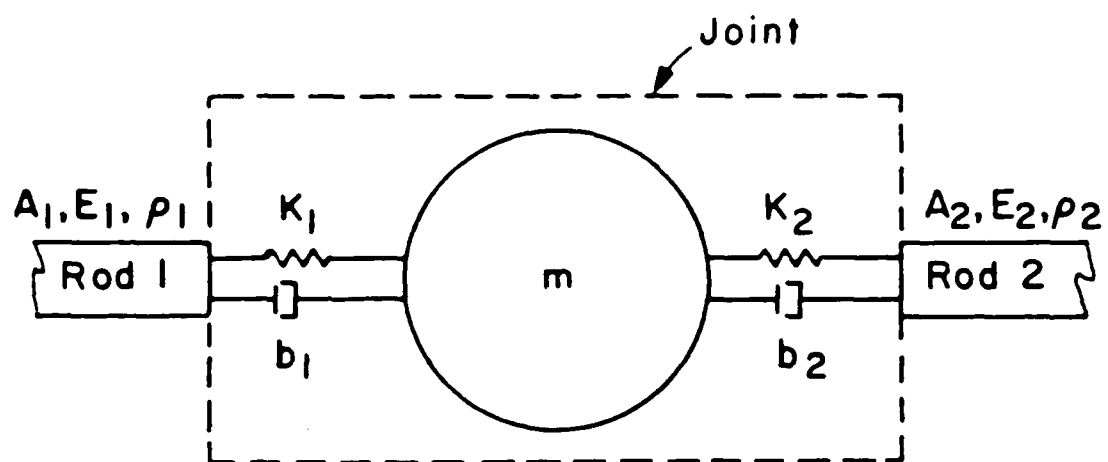
Phase velocity versus angle of incidence for SH wave travelling in tetrahedral truss plate.



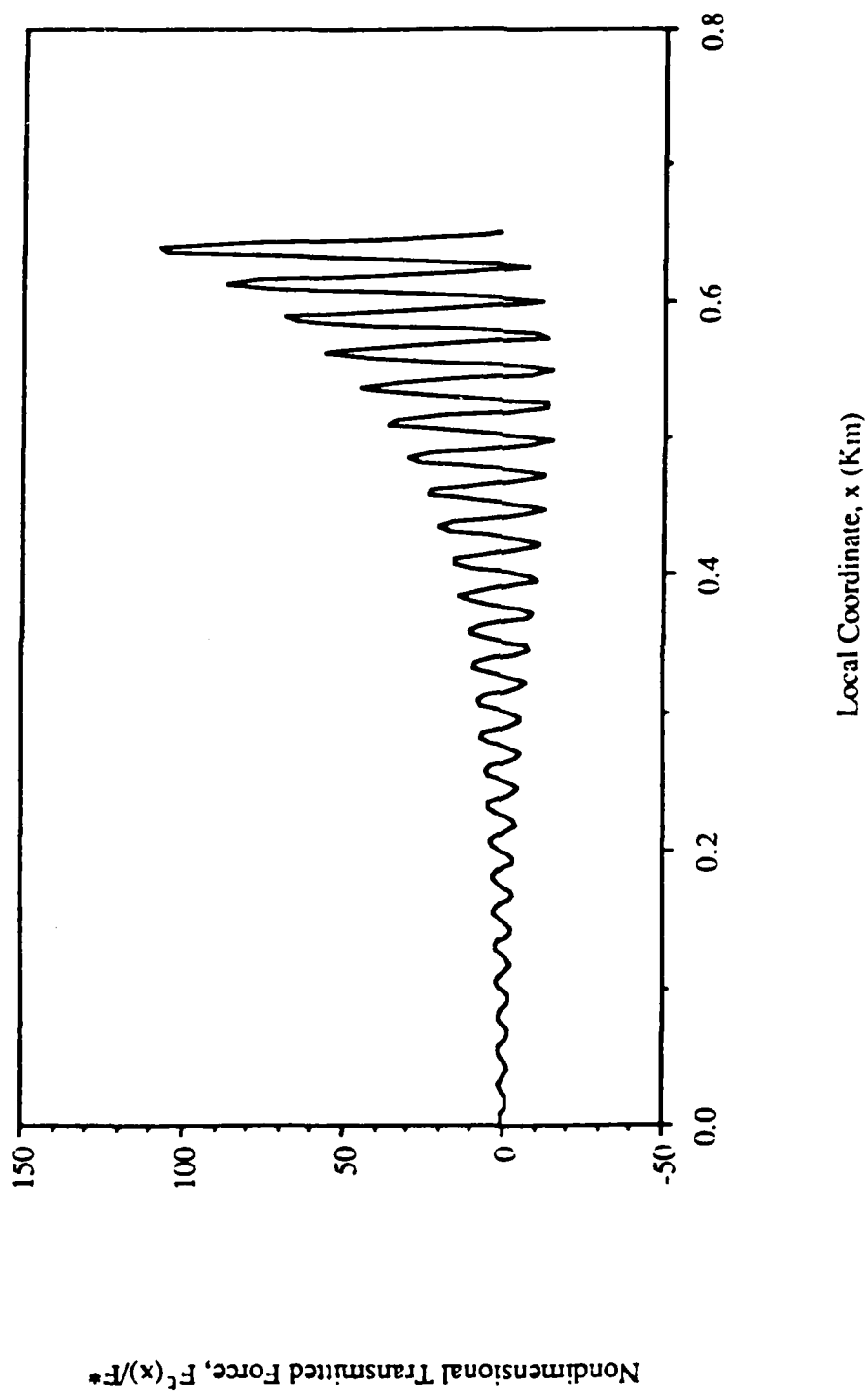
Path of SH - SH - ... wave which arrives at receiving transducer after n reflections from bottom boundary.



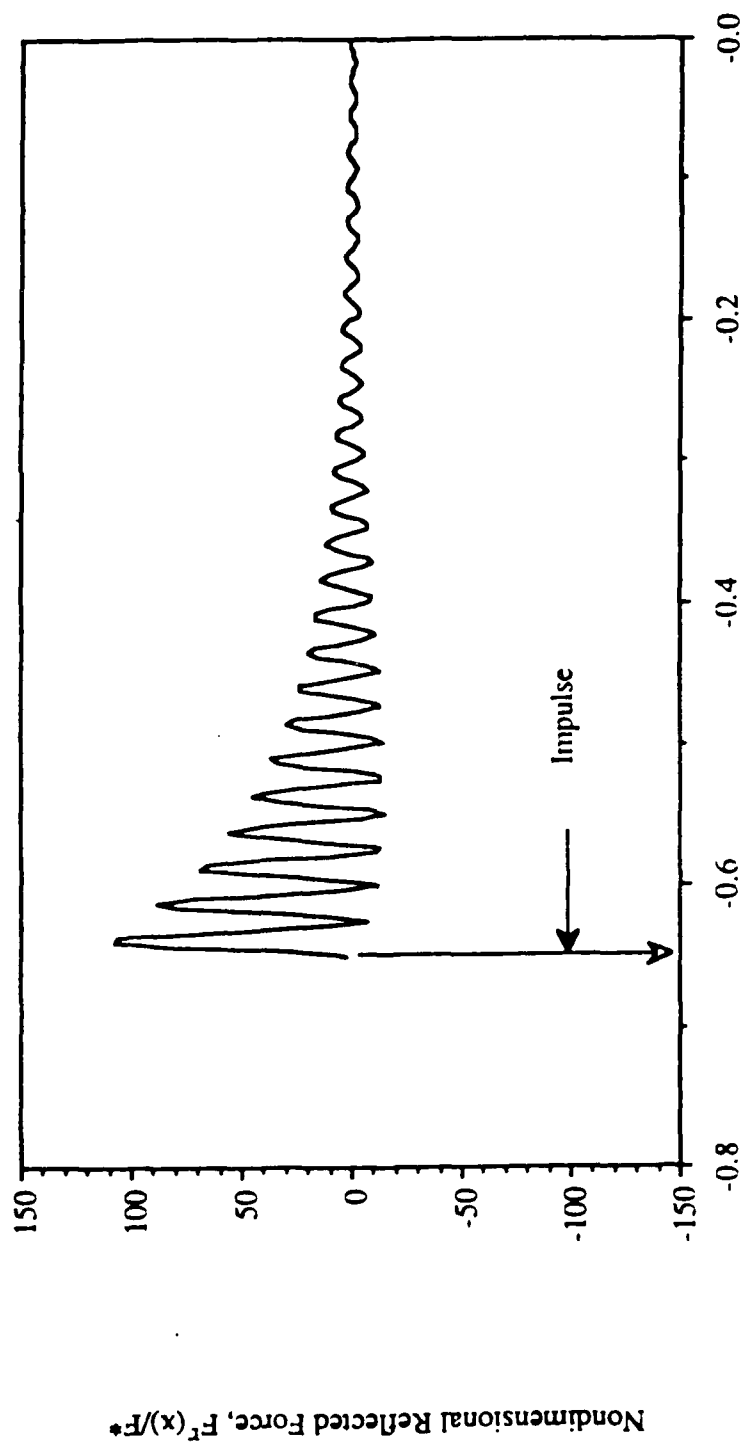
Delay time versus dimensionless separation (l/h) with number of reflections (n) from the bottom face of tetrahedral truss plate as parameter.



Model of joint connecting two elastic longitudinal rods.



Nondimensional transmitted force in lattice due to impulse
incident upon flexible joint ($\tau = 0.025$, $\omega_0 = 1240$ rad/s)
with mass.



Local Coordinate, x (Km)

Nondimensional reflected force in lattice due to impulse
incident upon flexible joint ($\zeta = 0.025$, $\omega_n = 1240$ rad/s)
with mass.

Single Degree of Freedom (Second-Order) System

Equation of motion:

$$m\ddot{x} + c\dot{x} + kx = 0$$

Or

$$\ddot{x} + 2\zeta\omega_n\dot{x} + \omega_n^2x = 0$$

where

$$\zeta = \frac{c}{c_c} = \frac{c}{2m\omega_n} \quad \omega_n^2 = \frac{k}{m}$$

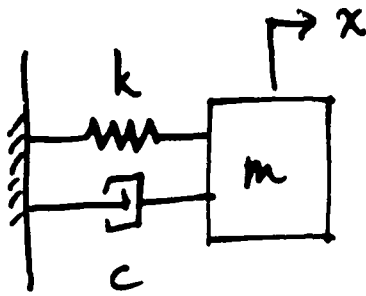
Assume

$$x(t) = Ce^{\lambda t} \implies \lambda^2 + 2\zeta\omega_n\lambda + \omega_n^2 = 0$$

$$\therefore \left. \begin{matrix} \lambda_1 \\ \lambda_2 \end{matrix} \right\} = (-\zeta \pm \sqrt{\zeta^2 - 1})\omega_n$$

Three Cases:

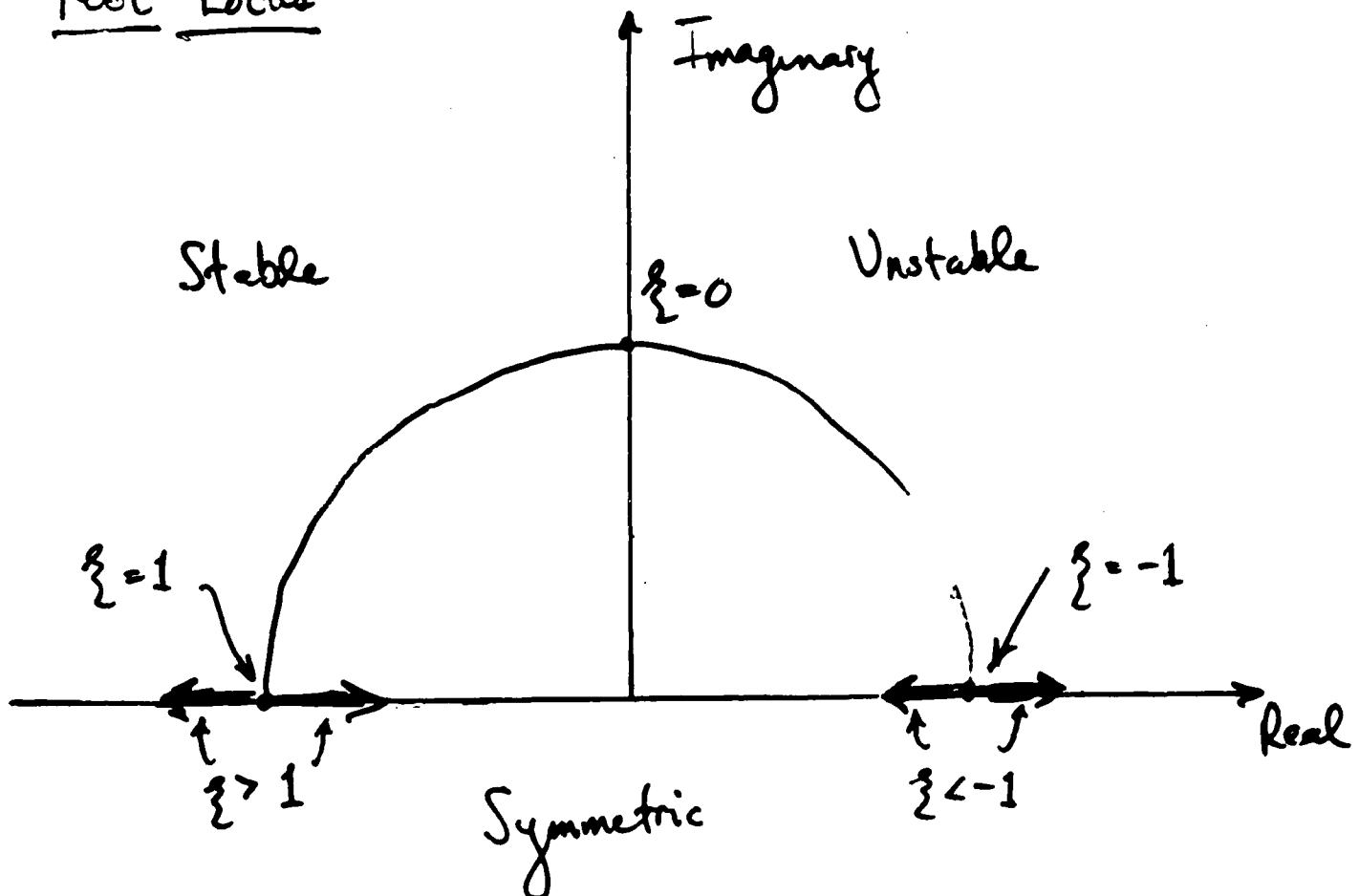
1. If $\zeta > 1$, roots are real, negative and distinct.
2. If $\zeta = 1$, roots are real, negative and equal.
3. If $\zeta < 1$, roots are complex conjugate with negative real part.



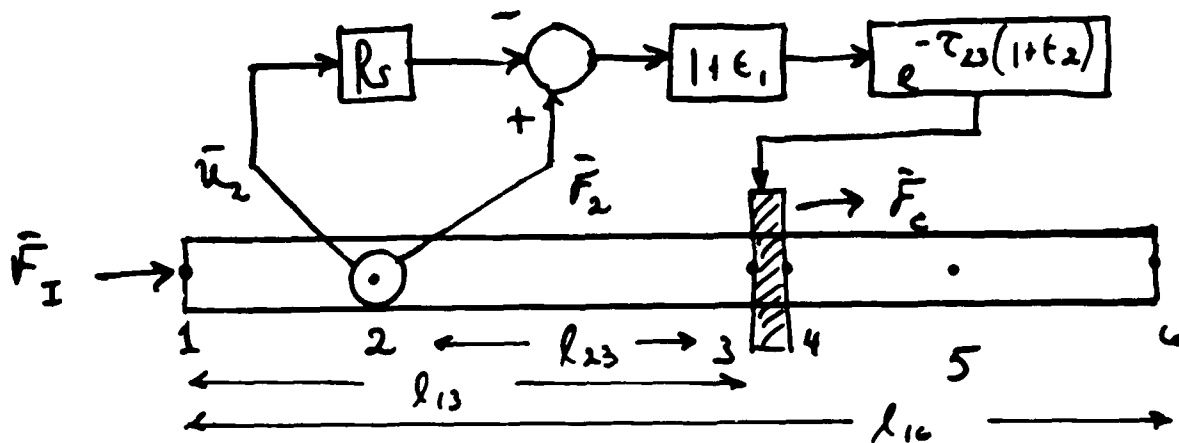
$$m\ddot{x} + c\dot{x} + kx = 0$$

$$\zeta = \frac{c}{2\sqrt{km}}$$

Root Locus



Wave Control



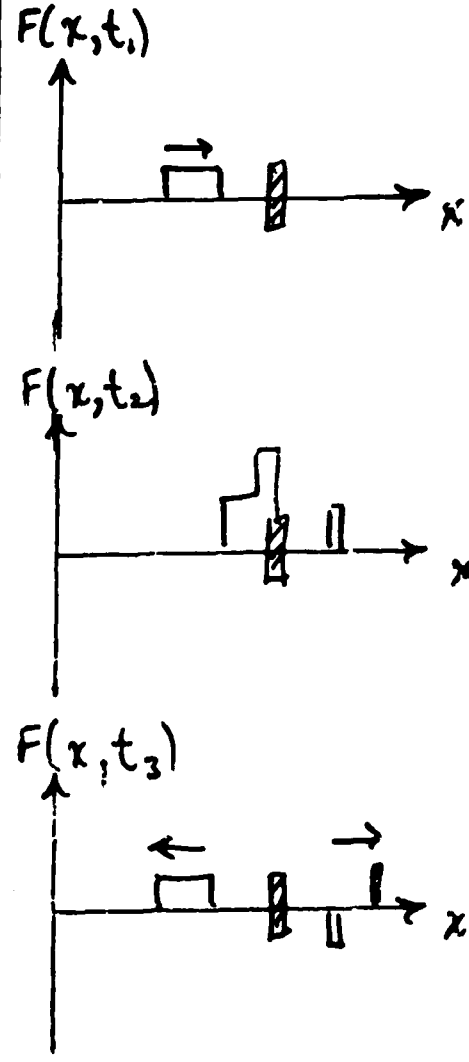
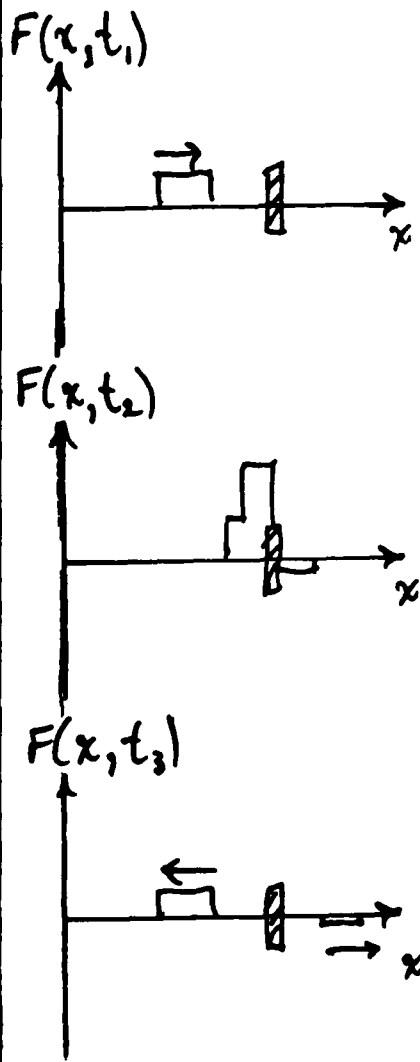
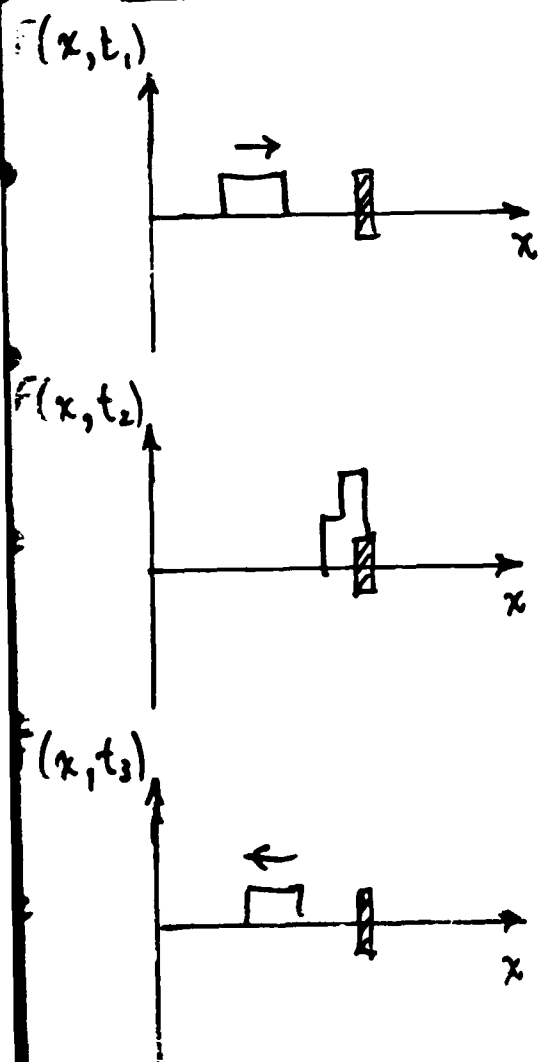
$$\epsilon_1 = \epsilon_2 = 0$$

$$\epsilon_1 \neq 0$$

$$\epsilon_2 = 0$$

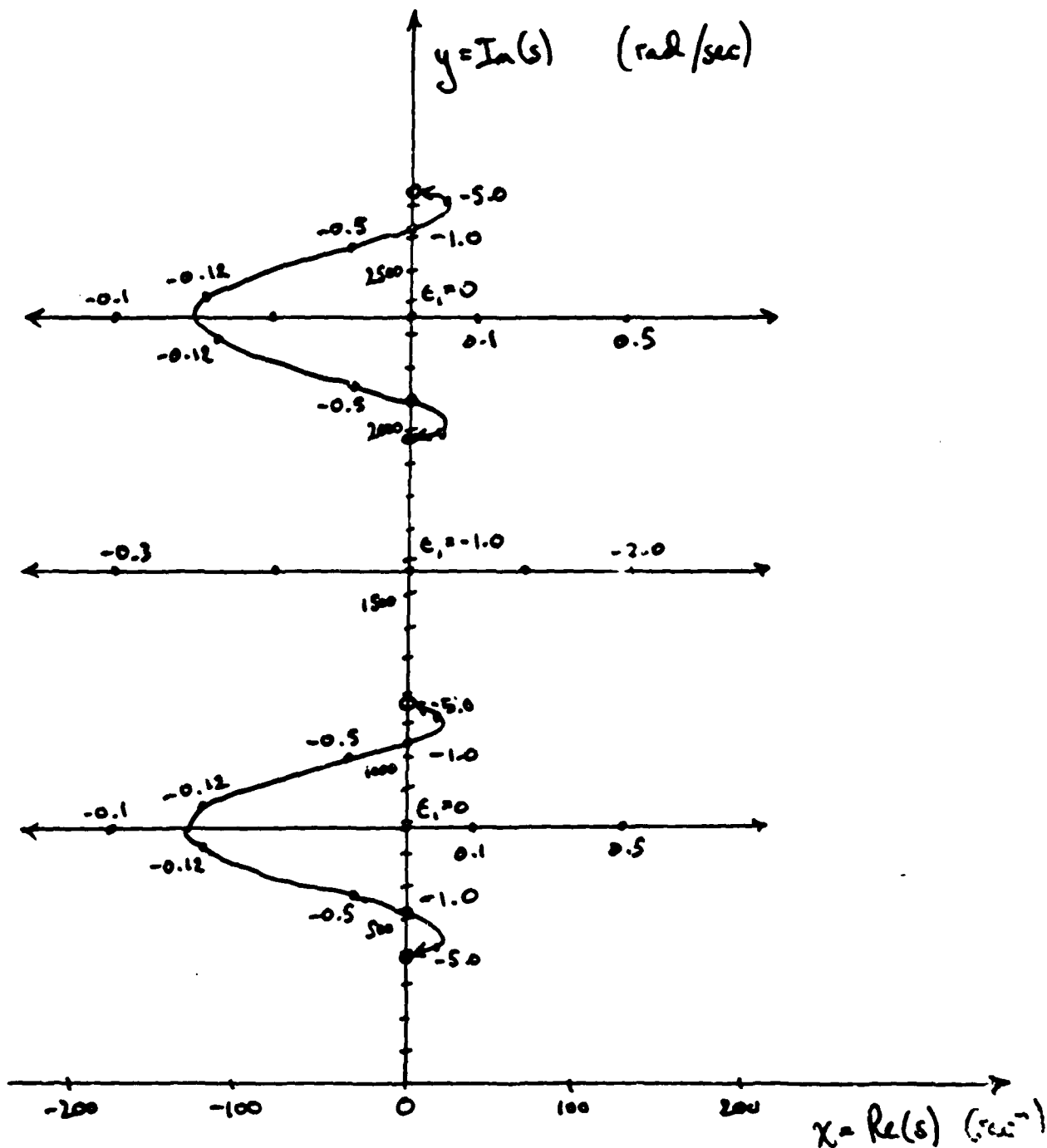
$$\epsilon_1 = 0$$

$$\epsilon_2 \neq 0$$



Root Locus as a Function of Amplitude

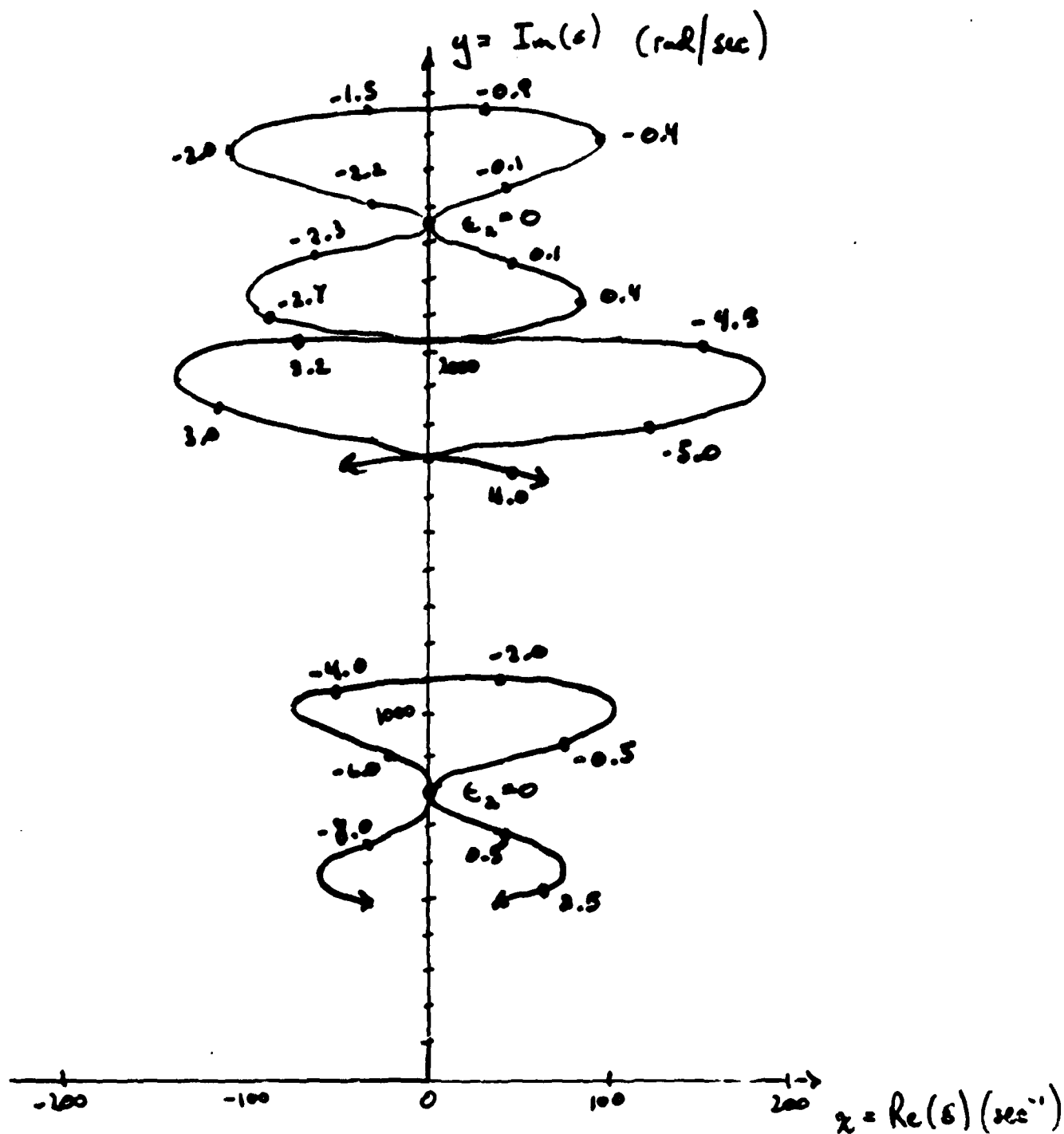
Error ϵ_1



$$\epsilon_2 = 0 \quad l_{13} = 10 \text{ m} \quad l_{23} = 6 \text{ m} \quad l_{16} = 30 \text{ m}$$

$$c = 5000 \text{ m/sec}$$

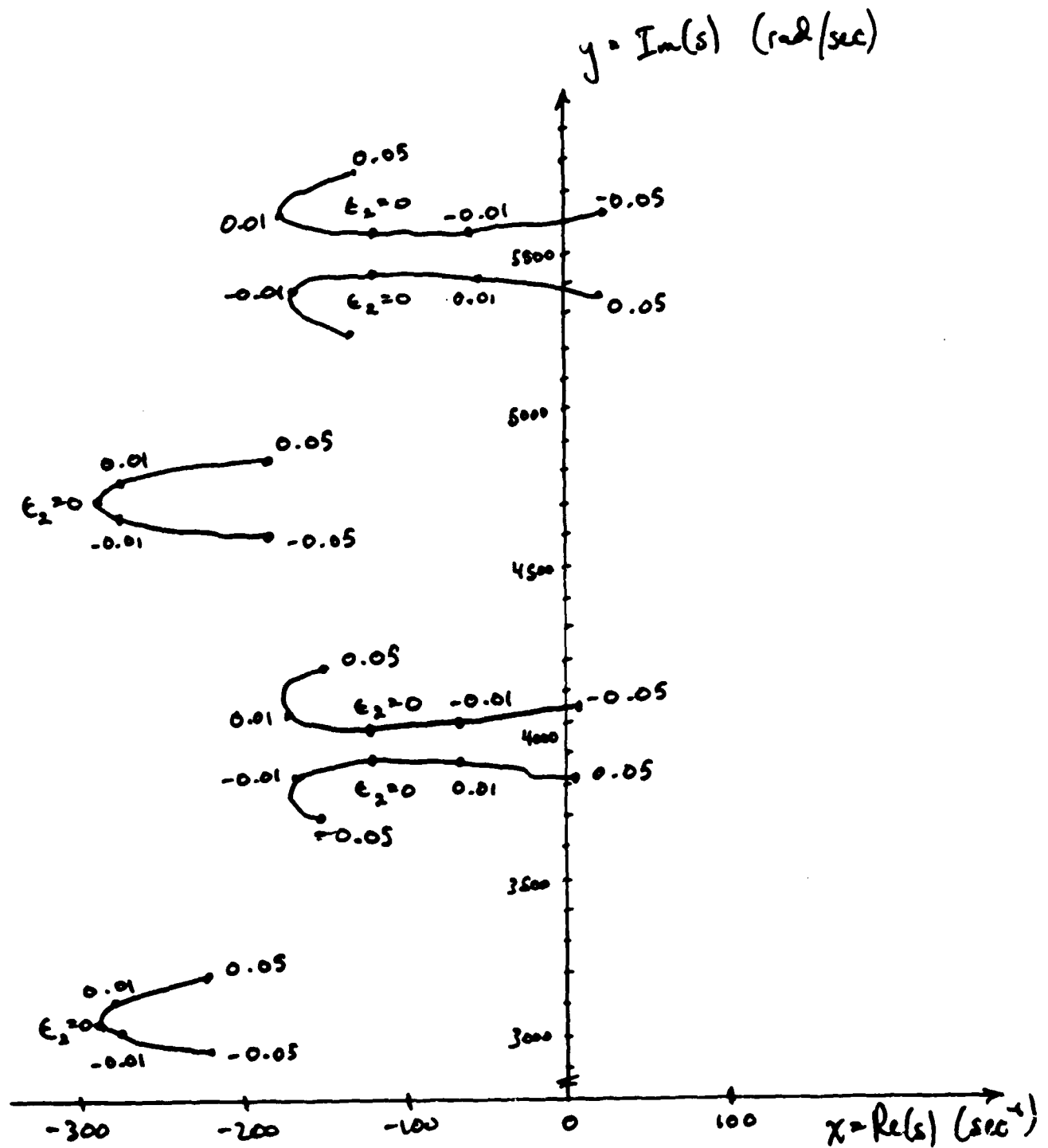
Root Locus as a Function of Tuning Error ϵ_2



$$\epsilon_1 = 0 \quad l_{13} = 10 \text{ m} \quad l_{23} = 6 \text{ m} \quad l_{16} = 30 \text{ m}$$

$$c = 5000 \text{ m/sec}$$

Root Locus as a Function of Tuning Error ϵ_2 for $\epsilon_1 = -0.12$



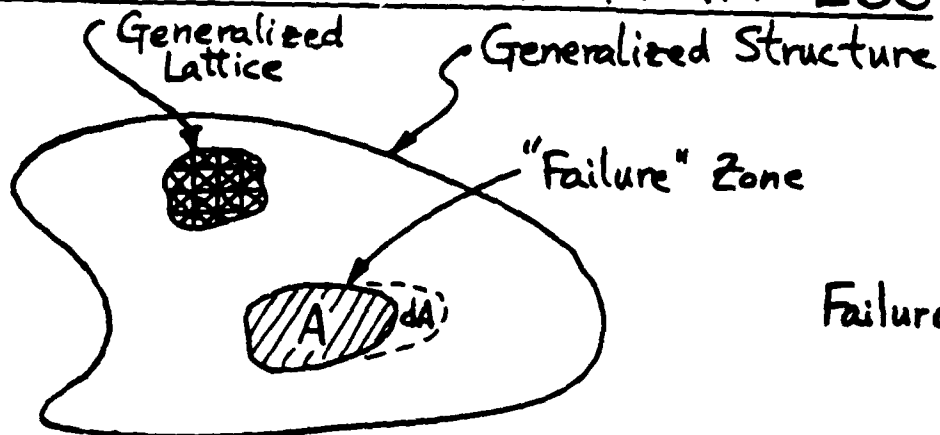
$$l_{13} = 10 \text{ m}$$

$$l_{23} = 6 \text{ m}$$

$$l_{16} = 30 \text{ m}$$

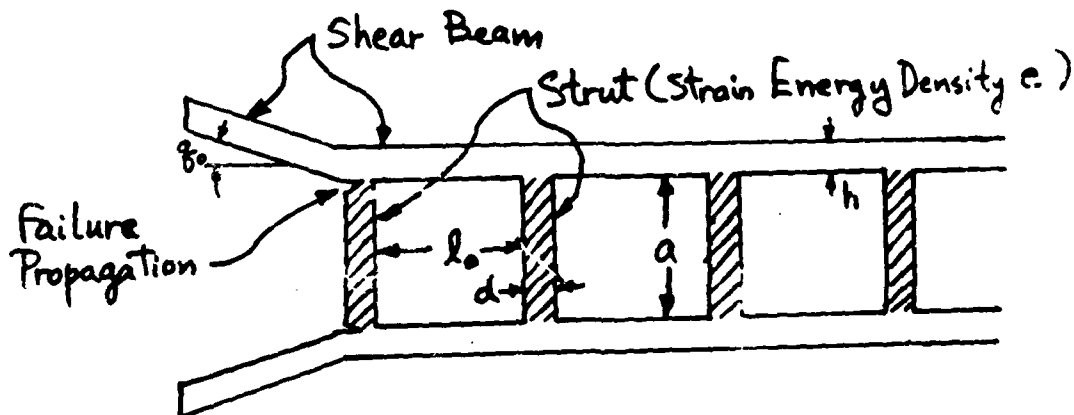
$$c = 5000 \text{ m/sec}$$

FAILURE PROPAGATION IN LSS



Failure = { Rupture
Buckling
LoJI
Etc. }

2-D Planar Lattice Model



Failure Propagation and Failure Arrest Criteria

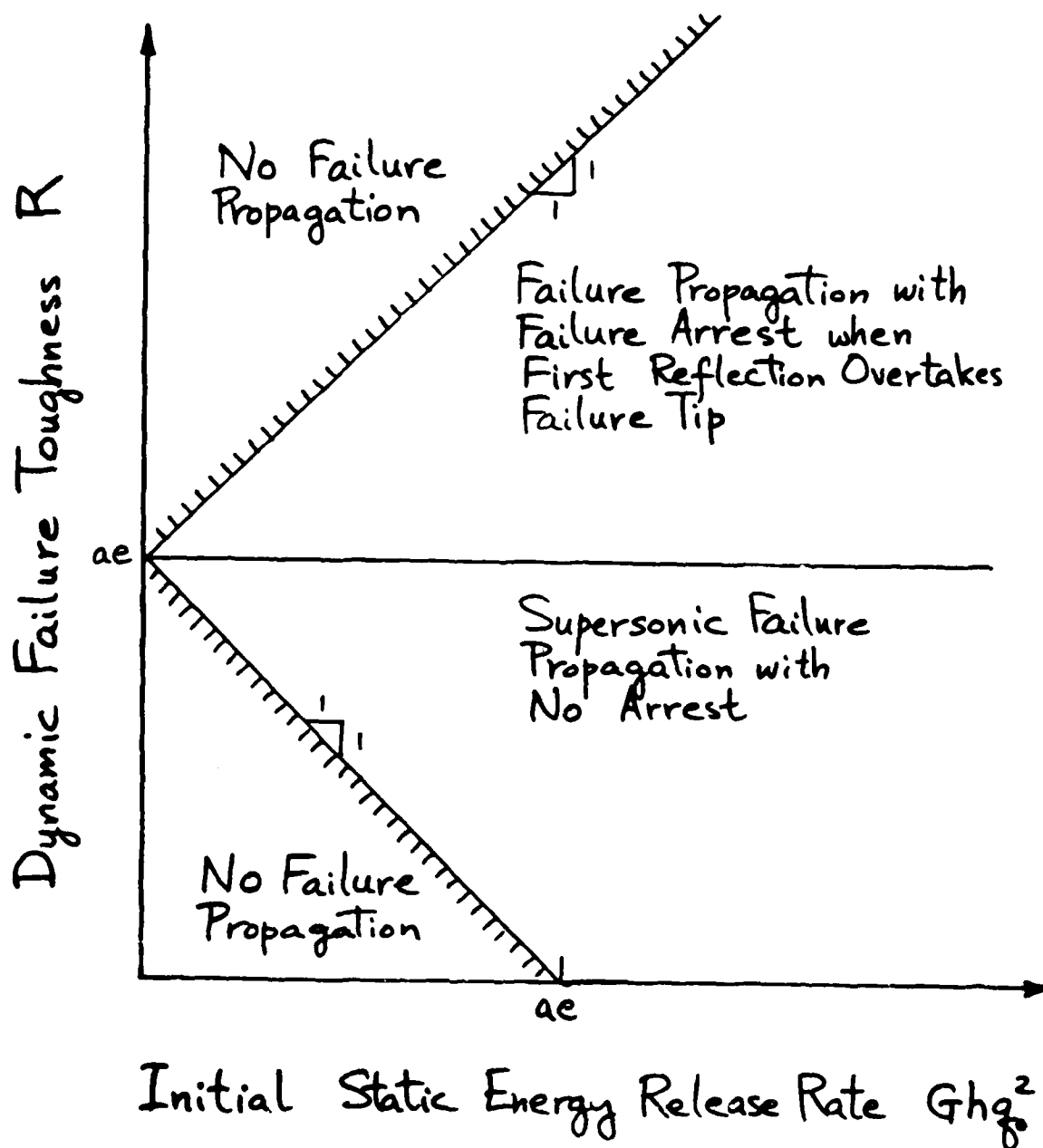
$$G_d = \frac{dW}{dA} - \frac{dV}{dA} - \frac{dT}{dA}$$

$G_d = R \rightarrow$ Failure Propagation (Domino Theory Fracture Mechanics)

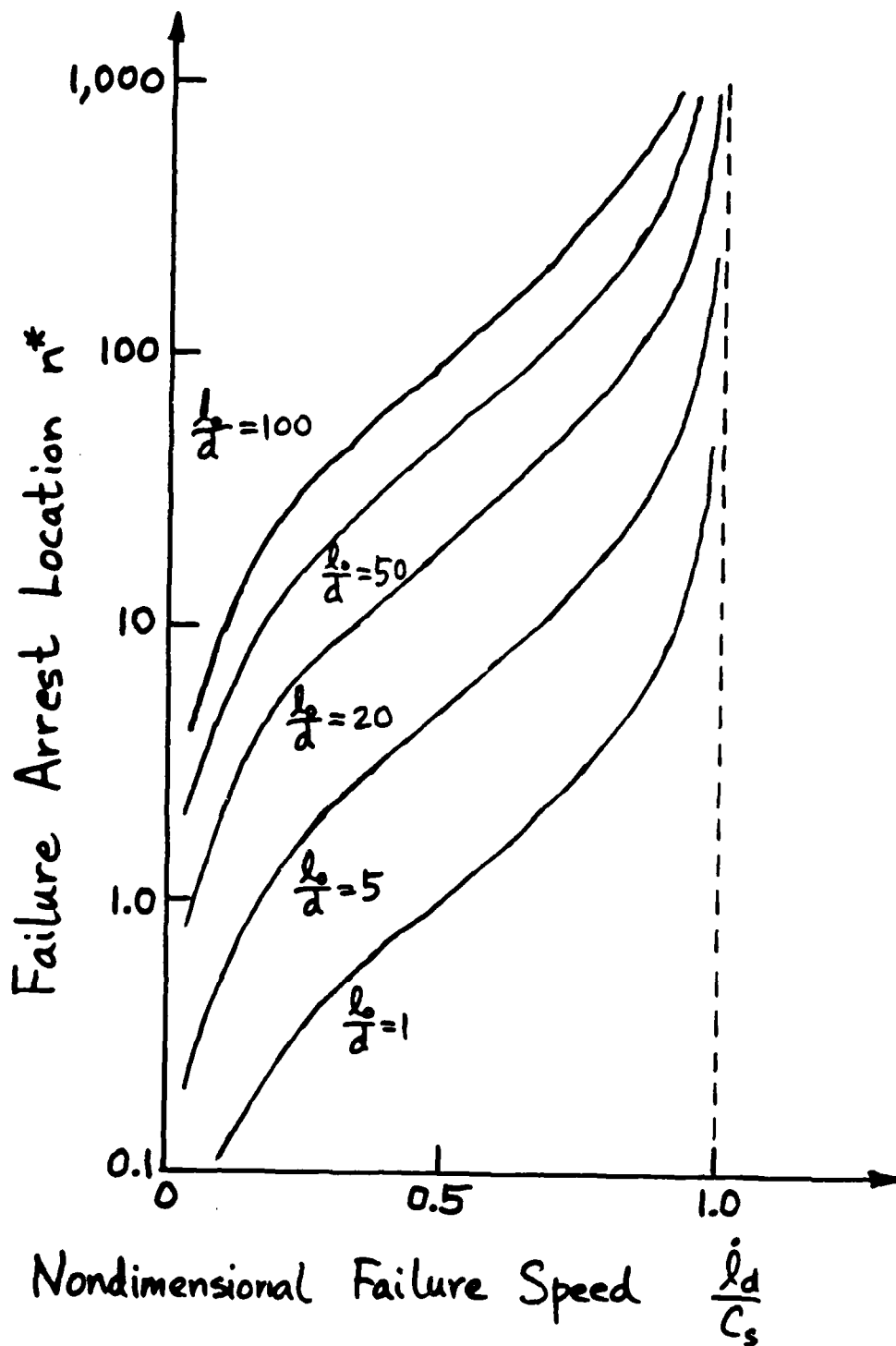
$G_d < R \rightarrow$ Failure Arrest

where G_d = Dynamic Energy Release Rate (Dynamic Failure Driving Force)
 R = Dynamic Failure Toughness

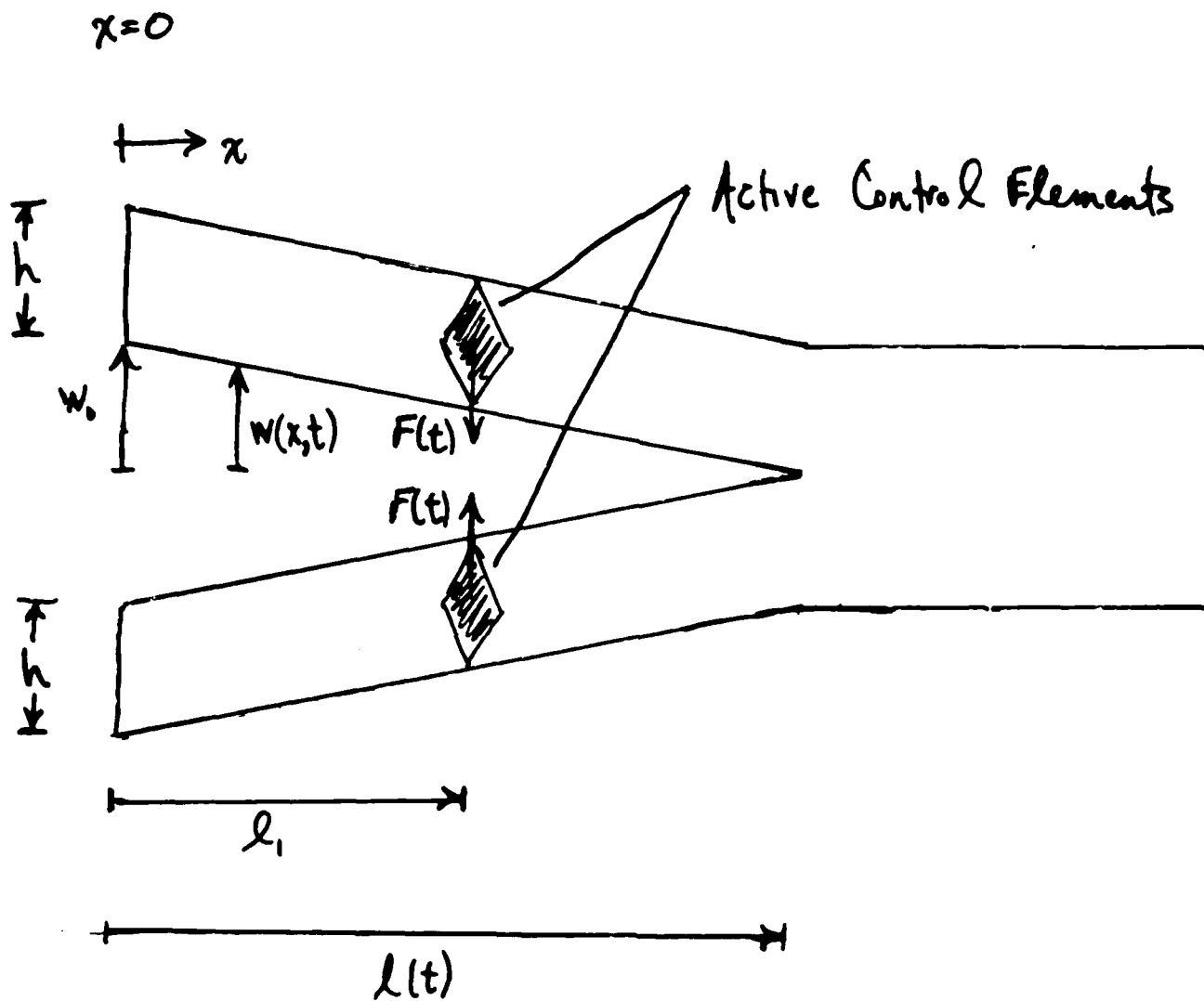
Criteria for Failure Propagation and Failure Arrest



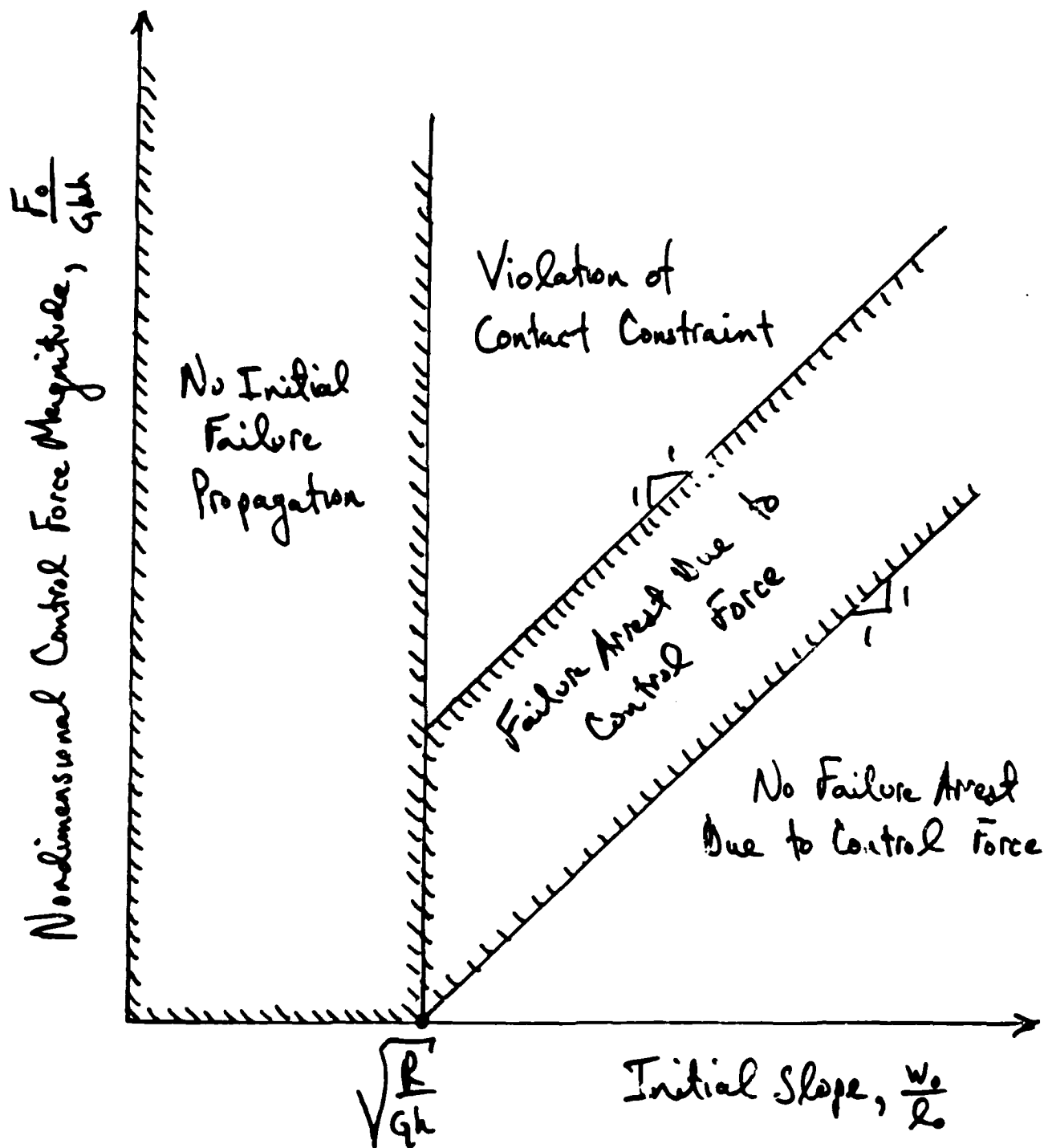
Location of Failure Arrest



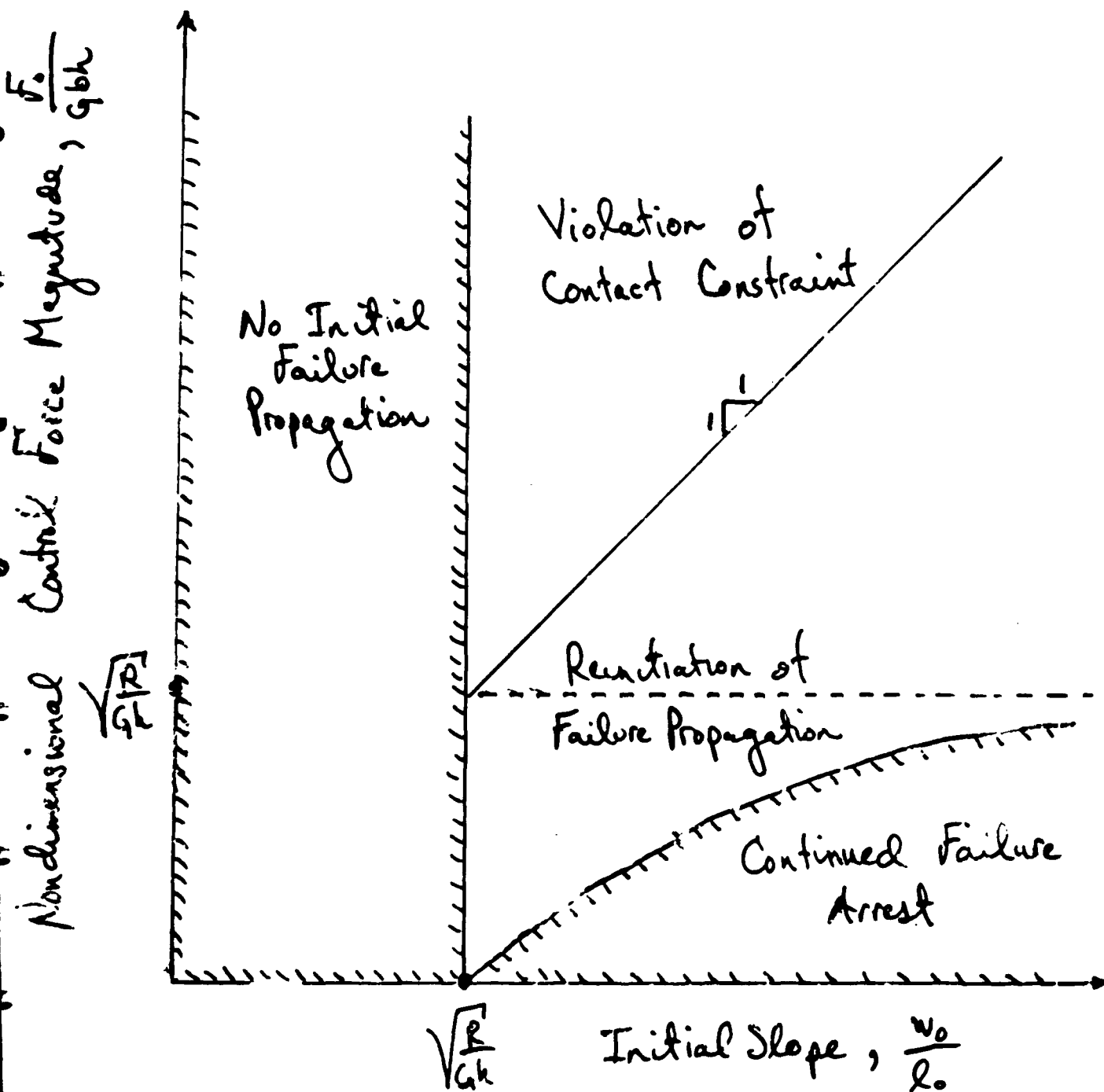
Control of Dynamic Failure



Failure Propagation and Failure Arrest Criteria



Criteria for Continued Failure Arrest or Reinitiation After Control Force is Removed



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